Dispersion Compensating Photonic Crystal Fiber with Enhanced Properties Achieved by Modified Core Geometry

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Abstract. *A novel dispersion compensating fiber based on photonic crystal fiber has been designed and studied in terms of optimal dispersion and operating bandwidth. The investigation of dispersion characteristics with respect to change in hole diameter and pitch has been provided. Further optimization of the designed fiber has been applied to the achieved fiber's properties in order to achieve a potentially easy-to-fabricate dispersion compensating fiber.*

Keywords

Dispersion compensation, finite difference frequency domain, chromatic dispersion, photonic crystal fiber, relative dispersion slope.

1. Introduction

Optical pulses propagating in an optical fiber are distorted owing to wavelength-dependent variation in propagation time of individual components of the optical pulse. This leads to pulse broadening and interference between subsequent pulses, which decrease the system performance. The mentioned undesired phenomenon is known as Chromatic Dispersion (CD) and consists of two components - material dispersion and waveguide dispersion. Material dispersion, which is positive for silica glass at telecom wavelengths, is related to material properties, fiber length and the width of spectrum of an optical source. Waveguide dispersion depends on the geometry of fiber, accuracy of fabrication and is influenced by the field distribution of the guided mode. It is possible to obtain overall negative CD of the fiber through high negative waveguide dispersion.

The design flexibility of Photonic Crystal Fibers (PCFs) for engineered dispersion is inherited in their strong correlation between design parameters and optical properties. Wider choice of material composition and arrangement of geometry of PCFs, compared to conventional Dispersion Compensating Fibers (DCFs), allow for dispersion compensation in the selected telecommunication band. The fine-tuned property can be extended by careful considered material composition of a background material, as well as of particular holes arranged in the fiber. Practical possibilities how to tailor dispersion characteristics of DCFs is limited, since requires a great accuracy. Therefore, all aspects of material technologies and fiber drawing should be concerned.

2. Related Works

A mature dispersion compensating PCF is characterized by high value of dispersion coefficient to allow for efficient compensation of CD in optical fibers, whilst keeping its length reduced to the minimum. Various design approaches to PCF-based compensation have been proposed. In principle, a DCF can be designed by using coupling modes in dual concentric cores [1], by doping the PCF's core [2], as well as by introducing small doped holes [3]. Submicrometer holes should be avoided, since their fabrication with the desired accuracy is impossible [4]. Huge deviations of predicted geometry can disqualify the drawn fiber for getting eventually applied in practical implementations. Achieved parameters of the commercially available PCFs confirm this claim [5]. The value of dispersion coefficient is one of the quantities monitors during every design process. In systems with WDM, an operating bandwidth is a critical design parameter. A fiber presented in [6] exhibits high value of dispersion coefficient being $-1120\ \mathrm{ps \cdot km^{-1} \cdot nm^{-1}}$, but achieved over a narrow wavelength range (approximately 20 nm), which makes the design unsuitable for broadband compensation of CD.

A high index contrast between doped core and pure background material is unacceptable by reason of physics, since the molecules of doping material diffuse from its original location to neighboring undoped regions [6]. A problem of fabrication may also result from the required precision of parameters' implementation. For example, the accuracy of hundredths of a micrometer can be necessary [7]. In addition, different diameters of holes in a fiber or varying pitch complicate the manufacturing process [7]. Therefore, the desired properties should be achieved by simpler fiber modifications, if possible.

A simple design of a DCF, based on Index Guiding Photonic Crystal Fiber (IGPCF), with a hexagonal lattice and solid core modified by insertion of a small hole into it is considered in [8]. The inclusion is smaller in diameter than other holes adjacent in the cladding. Since the parameters proposed in [8] are found to be problematic for practical implementation, the optimization of the considered models is necessary. Both are presented in the Results section of this paper.

3. Methods

The results presented in this paper were obtained using the full vectorial Finite Difference Frequency Domain method [9]. This method utilizes mesh to discretize the structure, effectively creating Yee computational cells, as an approximation of Maxwell curl equations. Values of field intensity vectors on edge and nodal positions of the mesh are arranged into matrices. Conformal mesh technique [10] is applied on the structure to account for curved interfaces between two different materials within a computational cell. This improves the accuracy of solution as Maxwell curl equations are only computed along respective material boundaries within the cell. The effective modal index n_{eff} and a field profile can be obtained at different frequencies by solving the matrices. A value of the effective modal index is used to compute dispersion, which is expressed as the dispersion coefficient D

$$D = -\frac{\lambda}{c}\frac{\partial^2 \operatorname{Re}\{n_{eff}\}}{\partial \lambda^2}\frac{1}{L}, \tag{1}$$

where λ is wavelength, c denotes speed of light in vacuum, and L is the length of fiber. Moreover, Dispersion Slope (DS) S is computed as a derivative of D with respect to wavelength as in (2).

$$S = \frac{\partial D}{\partial \lambda}. \tag{2}$$

For a concatenation of a SMF and a DCF exists equations, which consider their lengths and values of dispersion (3) and dispersion slope (4). Quantities for DCF are denoted with lower indices, whereas quantities without indices are related to SMF.

$$LD + L_{DCF}D_{DCF} = 0, \tag{3}$$

$$LS + L_{DCF}S_{DCF} = 0. \tag{2}$$

A definition of Relative Dispersion Slope (RDS) (5) can be given as based on (3) and (4). At best, values of RDS for SMF and DCF are equal, which represents ideal compensation.

$$RDS = \frac{S_{DCF}}{D_{DCF}} = \frac{S}{D}. \tag{5}$$

The wavelength range considered in simulations of dispersion characteristics is 1000-1800 nm. This choice of the range covers currently used C band, while also allowing for an extension to other wavelengths, considered for a potential usage of DWDM systems.

A fused silica glass is used as a background material of the designed fibers. The Dependence of refractive index on wavelength for silica is expressed by a Sellmeier dispersive formula (6) [11].

$$n^2 - 1 = \frac{0{,}6961663\lambda^2}{\lambda^2 - (0{,}0684043)^2} + \frac{0{,}4079426\lambda^2}{\lambda^2 - (0{,}1162414)^2} + \frac{0{,}8974794\lambda^2}{\lambda^2 - (9{,}896161)^2}. \tag{6}$$

4. Results

The small hole introduced into the solid core of IGPCF significantly influences the mode field distribution, as observed in Fig. 1. The mode field affects the first ring of air holes, and the maximum of intensity is situated around the edge of the inclusion, which is different from the mode field distribution in a standard PCF with a uniform core, where the maximum intensity is located in the center of the fiber's core.

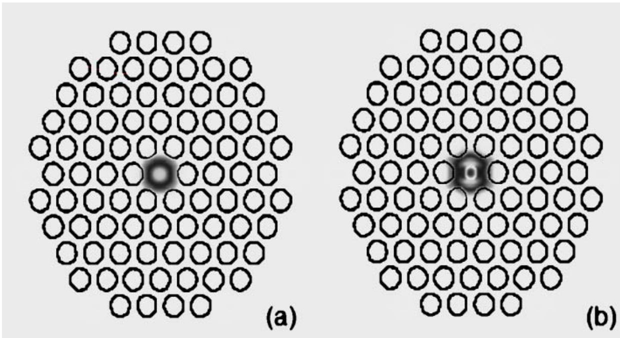

Fig. 1: Mode field distribution of IGPCF with a solid core (a) and with a modified core geometry (b).

The difference in wavelength-dependent dispersion characteristic, depicted in Fig. 2, is the result of altered waveguide dispersion, which is generally related to a mode field distribution. The wavelength-dispersion characteristic of the fiber with a hole in the core is linear with DS of approximately -22 ps·km^{-1}·nm^{-2} in the wavelength range of 1000-1700 nm. Moreover, the dispersion characteristic of the proposed PCF is more suitable for compensation of dispersion of SMF, owing to the higher negative value of dispersion coefficient D.

Tab.1: Design parameters of investigated PCFs.

Symbol	quantity	Value
n	refractive index of material at 1550 nm [-]	1,444
Λ	pitch [μm]	1,4
d	hole diameter [μm]	1,0
dc/Λ	normalized hole diameter of the core inclusion [-]	0,4
N_r	number of rings [-]	5,0

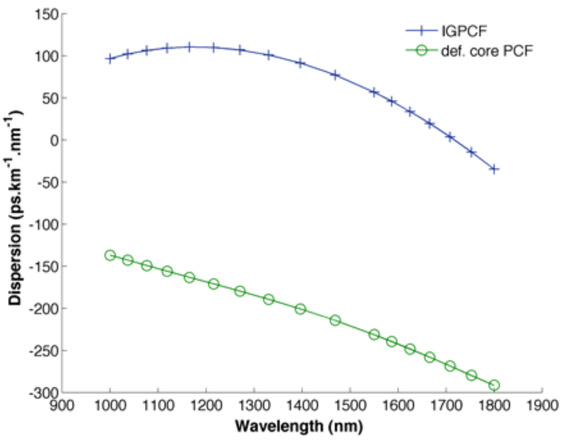

Fig. 2: Comparison of IGPCF with a solid core and investigated PCF with modified core geometry.

The following investigation of the dispersion characteristic with respect to change in particular parameters is performed. Such a parametric sweep is useful for the estimation of dispersion variation being the result of permitted tolerances of design parameters.

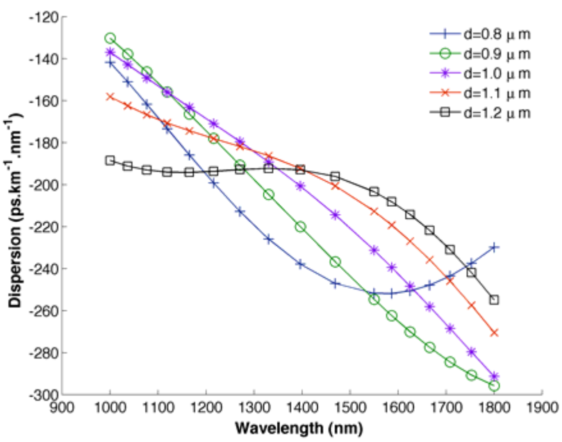

Fig. 3: Evolution of dispersion with respect to wavelength with a diameter of holes in the cladding as a parameter.

The dependency of studied fiber's dispersion on wavelength is depicted in Fig. 3. Cladding hole diameter is a parameter in this sweep. In this particular simulation, an increase in diameter is responsible for different slope and inflection of modeled dispersion evolution. A convex curve is obtained for small hole diameter, for a fiber with larger air holes takes a concave fashion. A curve closest to the linear function is achieved for 1-μm-diameter air holes. For the diameter value of 0,8 μm, the curve has a positive value of DS for wavelengths above 1550 nm, which makes it unsuitable for compensation of CD, since a typical SMF has a positive DS in this wavelength range.

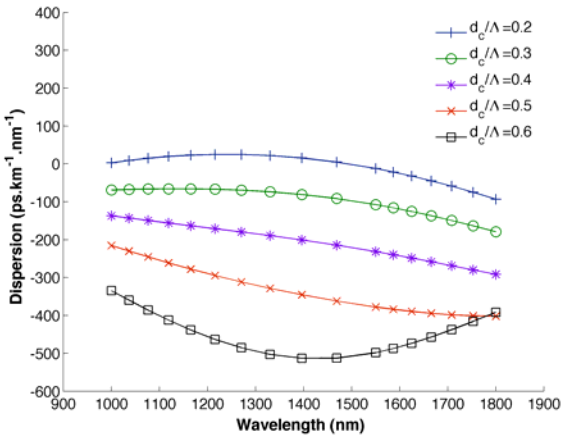

Fig. 4: Dependency of chromatic dispersion on wavelength with normalized hole diameter of the core inclusion as a parameter.

Investigated fiber's dispersion is less immune to potential adjustments of a core diameter, compared to the change in hole diameter of holes in the cladding. This results in strong correlation between size of the core hole and mode field profile, which influences directly waveguide dispersion properties. An expected intersection (intersections) of dispersion curves at a certain wavelength (wavelengths) for different values of the parameter is depicted in Fig. 4 (Fig. 3). This occurs, if different modes are propagated with the same waveguide dispersion. Then, the number of geometrical parameters of the fiber design for this wavelength is effectively reduced or, in other words, the design allows for a change in parameter due to its imprecision.

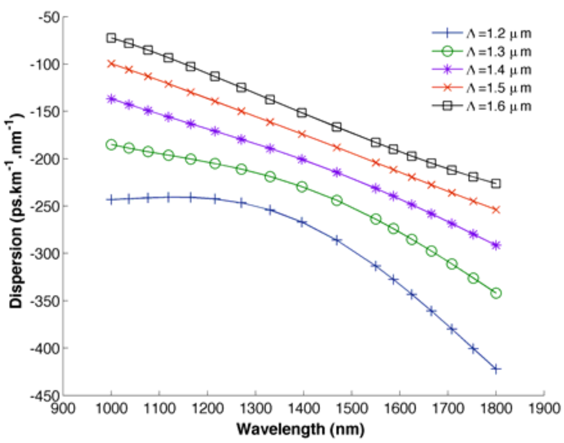

Fig. 5: Chromatic dispersion as a function of wavelength with value of pitch as a parameter.

Co-linearity in the dependency of dispersion on wavelength can be observed for pitch values in the range of 1,4-1,6 μm. A higher negative value of dispersion D is achieved by a selection of a small value of pitch. Nevertheless, the small value of pitch also restricts the use of large holes in the cladding. As far as the difference between value of pitch and value of the hole diameter is small, fabrication difficulties may emerge. On the contrary, the small difference implies that silica bridges among holes are narrow. Hence, it reduces the energy leaked from the core.

Tab.2: Parameters of optimized PCF.

Symbol	quantity	Value
n	refractive index of material at 1550 nm [-]	1,444
Λ	pitch [μm]	1,3
d	hole diameter [μm]	1,1
dc/Λ	normalized hole diameter of the core inclusion [-]	0,3
N_r	number of rings [-]	8,0

Gathered results are used as an input data for an optimization process. The optimization process of fiber's parameters is carried out in consideration of potential dispersion compensation. The goal of the optimization is to achieve the same value of RDS for both DCF and SMF at the 1550 nm wavelength. Values of geometrical parameters of the compensating fiber are controlled in the range suitable for fabrication. Dispersion of SMF is computed according to the third equation in [12] with constants, taken from the Corning SMF-28 fiber. This fiber is compliant with ITU-T G.652 recommendation and has a value of dispersion coefficient of 17 ps·km^{-1}·nm^{-1} at the 1550 nm wavelength. RDS is then computed based on (5). The parameters of the optimized compensating fiber are summarized in Tab. 2.

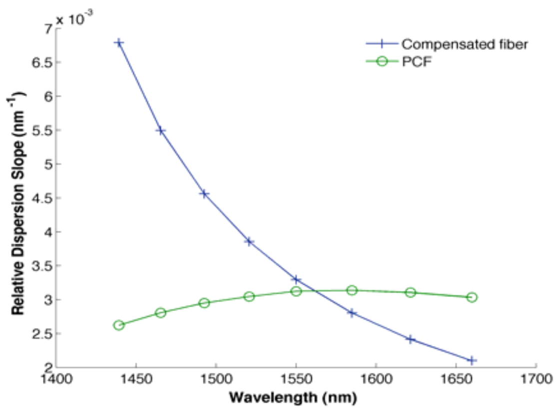

Fig. 6: RDS of compensating fiber after optimization process (smaller difference represents better compensation).

The optimized fiber exhibits an RDS value of 0,0031 nm^{-1} at the 1550 nm wavelength, whereas the SMF exhibits a RDS value of 0,0033 nm^{-1} at the same wavelength. In the wavelength range of 1530-1575 nm is the difference in RDS values below 10 %, which spans the whole optical C band. This RDS match means that both dispersion and dispersion slope of the considered type of SMF are effectively compensated.

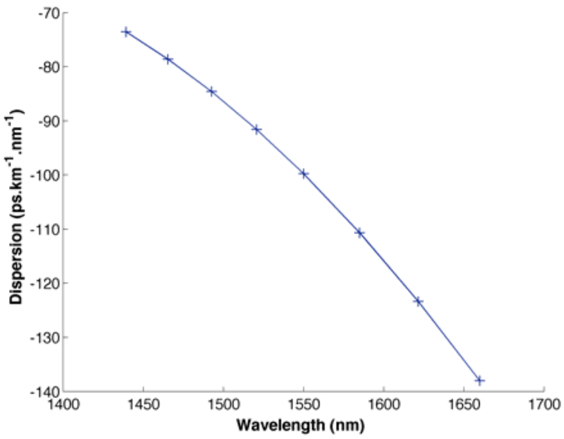

Fig. 7: Chromatic dispersion of compensating fiber after performing an optimization process.

The proposed optimized DCF has dispersion value of –100 ps·km^{-1}·nm^{-1} at the 1550 nm wavelength, which enables to compensate for chromatic dispersion of approximately six-time longer SMF than is the length of DCF.

5. Conclusion

A PCF suitable for dispersion compensation with a linear dispersion diagram in the area of negative values over a wide wavelength range is presented. Optimization of geometrical parameters of the proposed fiber is performed Presented optimized fiber is potentially suitable for fabrication. A future research would focus on the fiber's loss properties, since they are very attractive.

Acknowledgements

This work has been supported by the CTU grant under project SGS10/275/OHK3/3T/13.

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